# The PHENIX Detector Program at RHIC

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## Introduction

The relativistic heavy-ion collider (RHIC), located at Brookhaven National Laboratory (BNL), began operation in June 2000, with the collisions of co-rotating beams of high-energy gold ions at a center-of-mass energy of 140 GeV · A GeV. The principal goal of RHIC is to create extraordinarily hot and dense matter in the laboratory—matter such as is believed to have existed fleetingly in the first second following the big-bang beginning of the universe.

The sequence of pictures shown in Figure 1 visualizes this goal schematically. At the top, highly relativistic gold ions, shown as Lorentz-contracted disks, head towards each other and collide to form a new state of matter, shown in yellow. This matter is so hot and dense that the fundamental constituents of the protons and neutrons of the atomic nuclei—quarks and gluons—are free to roam over a volume the size of a gold nucleus. This hypothetical state of matter is termed the quark-gluon plasma (QGP). Demonstration of its creation in the laboratory and determination of its physical characteristics are the raison d'être of RHIC.

A second, very compelling program for which the RHIC collider is uniquely suited is the study of the spin structure of the nucleon. Thanks to technical developments made during the past 15 years, it is now possible to accelerate polarized protons in synchrotrons and maintain their polarization in storage rings. Thus with a modest investment in spin-manipulating equipment, RHIC will, for the first time, be able to produce collisions between polarized protons in the multi-hundred GeV range.

The spin structure of the nucleon, one of the least understood aspects of nucleon structure, has been extensively investigated with high-energy electron- and muon-proton collisions for the past ten years. However, many features of spin structure are intrinsically inaccessible with electromagnetic probes. The contribution to the spin the nucleon from gluons, the mediators of the strong interaction, is such a feature. Thus polarized-proton collisions will open significant new terrain in the examination of the structure of the nucleon at small-distance scales.

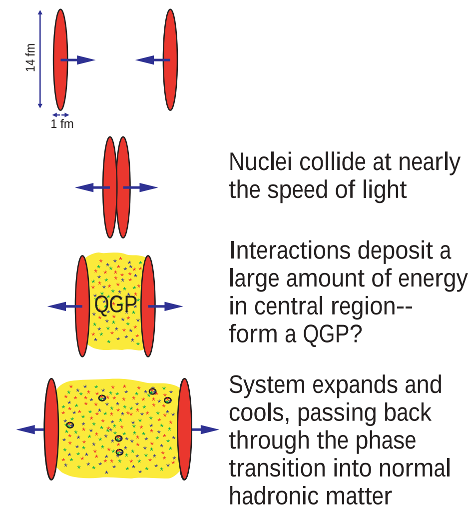


**Figure 1. Schematic evolution of a high-energy nucleus-nucleus collision. Starting at the top, we see two Lorentz-contracted nuclei move toward each other, collide, and the separation of the residual fragments in the bottom frame. The yellow region remaining is the hypothetical quark-gluon plasma.**

## Los Alamos National Laboratory's Role

The Physics Division's nuclear-physics program at Los Alamos National Laboratory (LANL) has been at the forefront of experimental work at high-energy accelerators since the mid 1980s. This included major involvement in the first high-energy heavy-ion collisions at CERN's (European Center for Nuclear Research) superproton synchrotron, and a few years later, the series of proton-nucleus experiments at Fermilab that led to the 1998 American Physical Society Bonner Prize in Nuclear Physics. These off-site efforts were clearly identified as LANL-led experiments. Much of the detector hardware, including electronic and data handling systems was designed and built at Los Alamos. LANL also hosted the subsequent analysis and interpretation of the data as well as the writing of the scientific papers.

Physics Division played a central role in the RHIC program, beginning in the early 1990s when collaborations were being formed to create the very large and technically complex devices required to diagnose ultra-relativistic heavy-ion collisions. In the years 1991–93, we helped form the collaboration and the physics program of the PHENIX detector (Pioneering High Energy Nuclear Interaction eXperiment), one of two large multipurpose collider detectors at RHIC. As with past off-site programs, LANL leadership is evident within the collaboration. We are the lead institution of two of the most technically challenging subsystems within he PHENIX detector, the muon spectrometer—largest of all the PHENIX detectors and the multiplicity and vertex detector (MVD), physically the smallest detector, but itself composed of some 35,000 channels of electronic readout.

In the mid 1990s, Physics Division initiated collaboration with physicists from the RIKEN Institute in Japan. This collaboration led to a significant investment of Japanese funding in the PHENIX detector (the south muon arm) and in the specialized magnets required to permit the acceleration and storage of polarized protons in RHIC. Thanks to this investment, the RHIC spin program became a reality. The construction of both the muon tracking system and the MVD required extensive interaction between Physics Division physicists and professional engineers during the conceptual design stages. Much of the engineering expertise was found in Los Alamos; within LANL in Engineering Sciences and Applications (ESA) Division, Nonproliferation and International Security (NIS) Division, and at HYTEC, a LANL spin-off company. Production of actual components involved Space Instrumentation and System Engineering Group (NIS-4), Subatomic Physics Group (P-25) personnel working at facilities both at LANL and BNL, and an array of outside institutions including the University of New Mexico (UNM); New Mexico State University (NMSU); the University of California, Riverside; and the Bahbba Atomic Energy Institute of India, as well as numerous firms in the private sector.

## Muon Tracking System Project

The muon tracking system consists of three planes of segmented-cathode multiwire proportional chambers, a technology developed in the Los Alamos Meson Physics Facility (LAMPF) program. Readout is accomplished by accurate determination of the image charge on cathode strips—hence the name cathode-strip chamber (CSC). Space points are determined by the three planes of CSCs that fix the radius of curvature of the tracks of charged particles moving through the magnetic field of the two PHENIX muon magnets. This measurement then leads to an accurate determination of the momentum of the particle. Figure 2 illustrates this concept, showing an elevation view that emphasizes the two-muon arms for the PHENIX detector with a simulated nucleus-nucleus collision.

We had to overcome a number of technical challenges to realize the goals of this project. First, the PHENIX muon magnets are very large, but with limited space available to contain the precision readout of electronic signals. The CSCs are divided into octants. The octants of the Station 3 chambers (largest planes at the extreme left and right in Figure 2) are about two meters tall, the largest CSCs ever built. Second, the middle CSCs (Station 2) are required tobe lightweight in order to minimize the degradation of the energy of charged particles whose momentum is measured by the tracker. To achieve this, the cathodes are formed from etched metalized Mylar foils, a technology pioneered at Los Alamos. The cathodes of Stations 1 and 3 are routed copper foils laminated to foam-composite boards.

The electronic readout of the CSCs is a particularly challenging task. In order to minimize electronic noise, the first stage of amplification must be very close to the chambers. This imposed severe electrical and mechanical constraints on the tracker, which is entirely contained within the two muon magnets. Nevertheless, by clever engineering design, some 20,000 channels of cathode readout were successfully constructed into each of the two muon-arm trackers.

The total project cost of the tracker is approximately $12 M; $7.3 M has come through the LANL financial system. The bulk of the remaining funding has been associated with the LANL-run facility at BNL. The construction project was successfully completed for the PHENIX south arm in January 2001. The tracking system for the north arm (for which funding arrived at a later date) is currently under construction at assembly factories at LANL, UNM, NMSU, and BNL. It will be installed and commissioned during 2002.

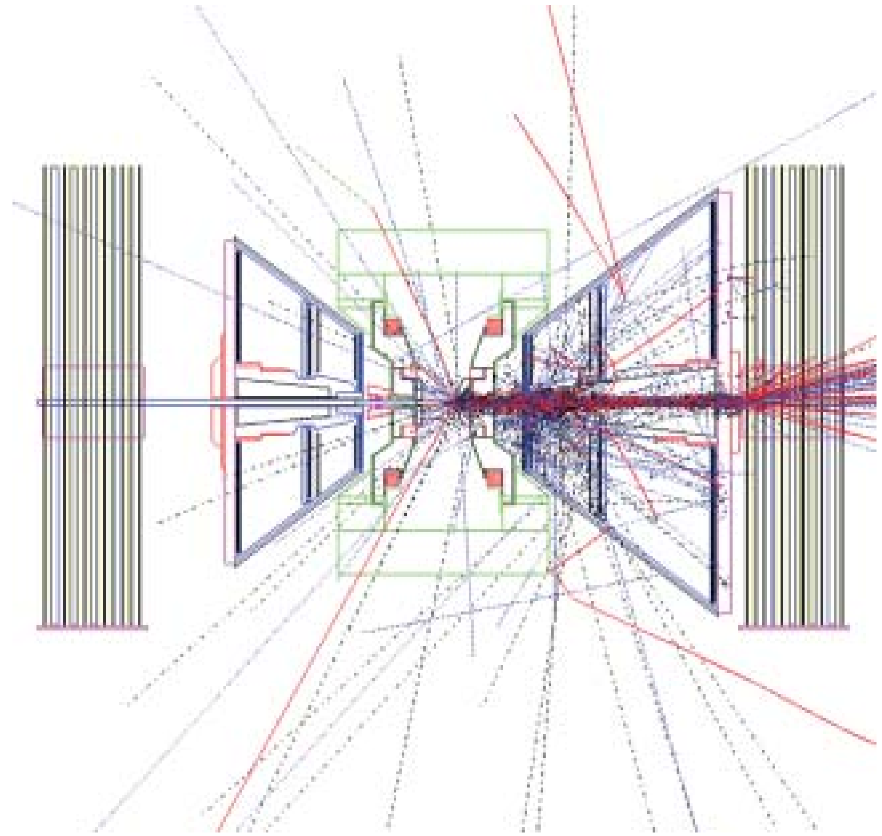

**Figure 2. Elevation view of the PHENIX muon arms superimposed with particle tracks from a simulated 100 GeV· A nucleus-nucleus collision. The muon tracker consists of three planes of CSCs that are located inside the two muon-arm magnets (trapezoidal elements on the left and right sides of the picture). To set the scale, the vertical structures to the left and right of the picture are 11-meter-tall plates of the muon identifier.**

## Physics with the PHENIX South Muon Arm during 2001

The completion of the south muon arm is an enormous success for LANL, achieved in the face of significant technical, financial, and temporal obstacles. It has been commissioned and will be ready for physics during the next running period of RHIC, currently scheduled to start in June 2001. Figure 3 shows the south arm in its staging area in early January 2001.

With collisions of gold ions at 200 A · GeV, RHIC presents a capability to create hot dense hadronic matter in the laboratory, which has never before been achieved. Thus, is it difficult to speculate what measurements to be made in the next few months will turn out to be most exciting. With its unique capability to detect muons, the PHENIX detector is in an enviable position among the four RHIC detectors.

A much-anticipated signal for the formation of the QGP is the suppression of the J/ψ resonance. This meson, composed of a charmed and anticharmed quark, is created readily in high-energy collisions. In a QGP however, very general arguments lead to the conclusion the J/ψ would be unstable, dissociating quickly into other particles.

Thus one of the most robust signatures of the successful formation of the QGP is the absence of the J/ψ most clearly seen through its distinctive decay in to a pair of oppositely charged muons. Although the absence of a signal seems to be an odd way to infer the presence of a new form of matter, experimental benchmarks exist that can be used to quantify the suppression of the J/ψ in central collisions of heavy ions. The most immediate is the production in peripheral collisions, where QGP formation is unlikely. Additionally one may examine collisions of lighter ions or of protons where QGP effects are either much reduced or absent altogether. Unlike many of the proposed signatures of the formation of the QGP, the J/ψ signal is quite robust, requiring little correction for nonphysics backgrounds.

The spin-structure program is also scheduled to begin operation during the last eight weeks of the RHIC 2001 running period. This will feature collisions of 200 GeV (in the center of mass) longitudinally-polarized protons. The south muon arm will be poised to make significant new measurements of polarization observables during this period. Because the luminosity (a measure of the intensity of collisions) will be comparatively low, there will be a premium on recording the rate of processes that have a large cross section. One such process that is likely to produce new information for the spin structure of the proton is open heavy-flavor production (open heavy flavor refers to hadrons that contain either a charm or bottom quark and one or two light quarks). Open heavy-flavor production should be observable through production of single muons with a large component of momentum perpendicular to the beam direction. According to detailed simulations of this process, the south muon arm should be capable of making a significant measurement of the contribution of gluon spin to the total spin of the proton within the next two years.

**Figure 3. The south muon arm of the PHENIX detector, shown in the staging area of the PHENIX detector hall.**

## The Multiplicity and Vertex Detector

The multiplicity and vertex detector (MVD) is a vital part of nearly every physics measurement made by the PHENIX detector. As its name suggests, its purpose is twofold:

1. to identify the point at which the colliding particles actually hit each other (collisions may actually occur anywhere in a region about a meter in length along the beam axis) and
2. to measure the multiplicity and distribution of charged-particle tracks from the collision.

The latter is a key measurement in the determination of the centrality of the collision. For example, gold ions that collide nearly head on produce as many as 7000–10,0000 charged particles, but collisions that are more peripheral in nature produce substantially fewer.

The MVD (Figure 4) consists of a large number of silicon detectors, microstrip detectors along the beam axis, and pad detectors at the two ends. There will be approximately 35,000 readout channels when it is fully instrumented in 2002. The MVD would be a simple detector to build if it were not for a very serious constraint that renders the project an exercise in state-of-the-art mechanical and electrical engineering. Because it is the first detector to intercept particles from the collision, and because other critical detector systems must determine charged-particle and photon energies at larger radii, the MVD must be nearly massless. Thus the detectors and their support system represent less than 1.5% of a radiation length of material along a particle's trajectory. The readout electronics are highly miniaturized in order to fit into small regions of the detection area that do not have active measurement elements.

Four years ago a large Class 10 clean tent facility was constructed and instrumented in SM-218 near the Physics Building in technical area (TA)-3 at LANL. All MVD prototyping and construction activities were carried out at this facility. One of the key elements of the MVD electronic readout system is a state-of-the-art device called a multichip module (MCM). The MCM packs the function of some 12 application-specific integrated circuits (ASIC) into a wafer of silicon about 2 cm square. Manufactured by Lockheed-Martin,

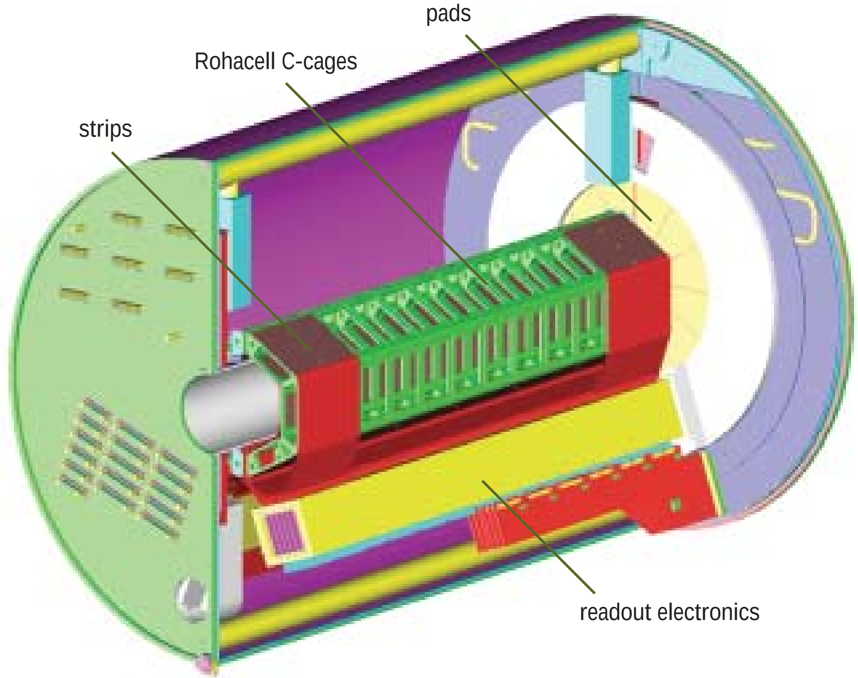


**Figure 4. Schematic view of the MVD. The green-hatched area at the center represents Rohacell foam C-cages (two opposing C-cages surround the beam axis) that hold the silicon-strip detectors, some of which are shown in maroon. At the two ends of the MVD are silicon pad detectors (yellow area at the right). The readout electronics are shown schematically as a yellow bar along the bottom of the MVD.**

the MCMs, when constructed correctly, achieve an incredible miniaturization of electronic components. Unfortunately, the manufacturing process has achieved a success rate of only ~40%. This has resulted in a significant cost growth of the MVD system and a consequent delay in its final implementation into the PHENIX detector. During the 2000 RHIC running period, a scaled-down version of the MVD, comprising about 25% of the total system was successfully installed and operated. We expect that the remaining 75% will be installed in PHENIX for the 2001 running period.

## Physics with the Multiplicity and Vertex Detector

The MVD's determinations of vertex and collision centrality are critical features of nearly every measurement of the PHENIX detector. However, in two areas the MVD alone can provide important data. In central collisions of heavy ions, a measurement of the multiplicity leads via a well-established relation (called the Bjorken formula) to a determination of the energy density achieved in the collision. This measurement can be made, in principle, from a single central collision. In addition, the MVD on its own can be used to search for fluctuations in the pattern of charged-particle production, predicted to occur in some theories of the phase transitions that may occur in high-energy heavy-ion collisions.

**Figure 5. Multiplicity and vertex detector during assembly at Brookhaven in June 2000. One of two Rohacell C-cage assemblies is shown in the vertical position (horizontal in Figure4) with some of the strip detectors and kapton cables attached.**

## Summary and Outlook

The RHIC era opens a qualitatively new chapter in accelerator-based physics. Never before has the capability existed to examine the results of ultrahigh-energy collisions of the heaviest elements (Previous results from the CERN SPS fixed-target program were obtained at center-of-mass energies an order of magnitude lower.) Similarly, RHIC offers for the first time, the capability of examining detailed structures of the nucleon that depend on the spin orientation of its fundamental constituents—quarks and gluons. For these reasons the next few years promise much exciting new physics with the new instruments conceived and built by LANL personnel.

## Further Reading

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